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Magnetic Fields on Cool Stars

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Abstract. Magnetic fields are an important ingredient to cool star physics, and there is great interest in measuring fields and their geometry in order to understand stellar dynamos and their influence on star formation and stellar evolution. During the last few years, a large number of magnetic field measurements became available. Two main approaches are being followed to measure the Zeeman effect in cool stars; 1) the measurement of polarized light, for example to produce magnetic maps, and 2) the measurement of integrated Zeeman broadening to measure the average magnetic field strength on the stellar surface. This article briefly reviews the two methods and compares results between them that are now available for about a dozen M-type stars. It seems that we see a great variety of magnetic geometries and field strengths with typical average fields of a few kG in active M-type stars. The interpretation of geometries, however, has not yet led to a clear picture of magnetic dynamos and field configuration, and work is needed on more observational data but also on the fundamental understanding of our measurements.

1. Introduction

The Sun and cool stars are known to harbor magnetic fields leading to all phenomena summarized under the term *stellar activity*. It may be debatable whether magnetic fields are actually the most interesting aspect of cool star and solar physics (cp. Moore & Rabin 1985), but it is certainly an exciting field that brings together a large variety of physical mechanisms and subtle analysis techniques. This makes it sometimes difficult to interpret observational results and compare them to theoretical expectations – even if both are available, or even if one compares observations achieved from different techniques.

A particularly interesting class of stars are cool stars of spectral type M. Covering the mass spectrum between ~ 0.6 and $0.1 M_{\odot}$, M dwarfs are the most frequent type of stars. Within this mass range, objects can have very different physical properties. The very important transition from partly convective (sun-like) to fully convective stars happens in the M dwarf regime, probably around spectral type M3/M4. Furthermore, atmospheres of M dwarfs can be very different and both molecules and dust gain importance as the temperature drops toward late spectral types.

In this article, I will concentrate on measurements of magnetic fields on M dwarfs because most of the currently available measurements of cool star magnetic fields are from M dwarfs, which is because sun-like (field) stars tend to be less active (less rapidly rotating because of shorter braking timescales) implying lower average magnetic fields that are more difficult to detect.

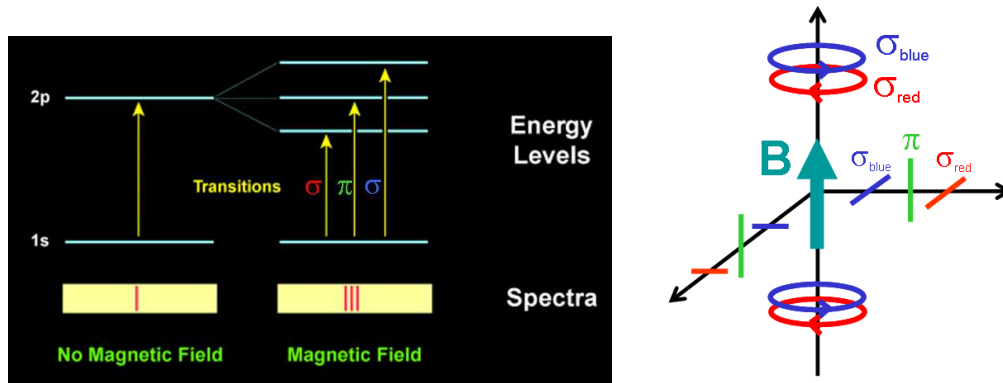


Figure 1. Schematic view of Zeeman splitting. The upper level in the example (left panel) is split into three levels producing three spectral lines that are separated. The polarization of the π and σ components are shown in the right panel.

2. Technical aspects

To measure the magnetic fields of stars, determination of spectral line splitting due to the Zeeman effect is the most commonly used method. In this article, I will not give a comprehensive overview of the Zeeman technique but try to emphasize a few technical aspects that are particularly important for the interpretation of the currently available measurements. More comprehensive discussions and reviews on magnetic fields and their measurement in cool stars are, e.g., Landstreet (1992); Valenti et al. (1995); Mestel & Landstreet (2005); Donati & Landstreet (2009); Miesch & Toomre (2009), or the conference reviews by Saar (1996); Johns-Krull (2008).

In short, dipole transitions obey the selection rule $\Delta M = -1, 0$ or $+1$. The three groups of lines according to different ΔM are degenerate if no magnetic field is present, but separated in the presence of a magnetic field. Transitions with $\Delta M = 0$ are called π -components, $\Delta M = \pm 1$ are called σ -components. If a magnetic field is present, the energy (wavelength) of the σ -components are shifted according to the sensitivity of the transition (summarized in the *Landé*-factor g), the strength of the magnetic field B , and the wavelength of the transition itself (λ_0). The average velocity displacement of the spectral line components can be written as

$$\Delta v = 1.4 \lambda_0 g B, \quad (1)$$

with B in kG, λ_0 in μm , and Δv in km s^{-1} . Fig. 1 shows a simplified scheme of the splitting (left panel) and of the polarization (right) of the π and σ components; the π component is always linearly polarized while the σ components can be linearly or circularly polarized depending on the viewing angle.

In order to measure a magnetic field, the measurement of different polarization states can be of great advantage. This is immediately clear from the right panel of Fig. 1 since the different Zeeman components are polarized in a characteristic fashion. A commonly used system are the Stokes components I, Q, U, and V, which are defined in the following sense:

$$\begin{array}{rclcl}
I & = & \updownarrow & + & \leftrightarrow \\
Q & = & \updownarrow & - & \leftrightarrow \\
U & = & \swarrow \searrow & - & \nearrow \nwarrow \\
V & = & \odot & - & \otimes
\end{array}$$

Stokes I is just the integrated light (unpolarized light), Stokes Q and U measure the two directions of linear polarization, and Stokes V measures circular polarization. It has been shown that the magnetic field distribution of a star can be reconstructed from observations of all four Stokes parameters (Kochukhov & Piskunov 2002; Kochukhov et al. 2010), and that using only a subset of Stokes vectors leads to ambiguities that should be interpreted with caution. Unfortunately, measurements of linear polarization are extremely challenging in cool stars so that typically only Stokes I and (sometimes) Stokes V are available.

2.1. Field, flux, and filling factor

The situation shown in Fig. 1 is simplified. In most cases, line splitting is a bit more complicated, but the main difficulty in measuring the splitting is the small value of $\Delta\nu$ compared to other broadening agents like intrinsic temperature and pressure broadening, and rotational broadening. In a kG-magnetic field, typical splitting at optical wavelengths is below 1 km s^{-1} , which is well below intrinsic line-widths of several km s^{-1} and also below the spectral resolving power of typical high-resolution spectrographs. Thus, individual components of a spectral line can normally not be resolved even if the star only had one well-defined magnetic field component. Real stars, however, can be expected to harbor a magnetic field distribution that is much more complex than this. Thus, even if spectral lines were intrinsically very narrow and spectral resolving power infinitely high, we would expect the Zeeman-broadened lines to look smeared out since in our observations we integrate over all magnetic field components on the entire visible hemisphere.

An important consequence of the fact that individual Zeeman-components are usually not resolved is the degeneracy between magnetic field B and filling factor f . A strong magnetic field covering a small portion of the star looks similar to a weaker field covering a larger portion of the star. An often used way around this ambiguity is to specify the value Bf , i.e., the product of the magnetic field and the filling factor (if more than one magnetic component is considered, Bf is the weighted sum over all components). Products of B with some power of f , for example $Bf^{0.8}$ are also considered because they seem to be better defined by observations (see, e.g., Valenti et al. 1995, for a deeper discussion). One important point to observe is that Bf is often called the “flux” – because it is the product of a magnetic field and an area – but it has the unit of a magnetic field. In fact, the term flux is very misleading since 1) Bf is identical to the average magnetic field on the stellar surface, i.e., $Bf \equiv \langle B \rangle$, and 2) the total magnetic flux of two stars with the same values of Bf can be extremely different according to their radii because the actual flux is proportional to the radius squared; $\mathcal{F} \propto Bfr^2$. As a consequence, the value Bf will be much lower in a young, contracting star compared to an older (smaller) one if flux is conserved.

A related source of confusion is the difference between the signed magnetic field (or flux), and the unsigned values or the square of the fields (used to calculate magnetic energy). With Stokes I, both polarities produce the same signal and only the unsigned flux is measured. This implies that Stokes I carries only partial information about field geometry, but it also means that Stokes I always probes the entire magnetic flux of the

star. On the other hand, Stokes V can provide information on the sign of the magnetic fields, but this comes with another serious caveat: Since we cannot resolve the stellar surface, and Stokes V measures the signed field, regions of opposite magnetic fields on the stellar surface cancel out and can become invisible to the Stokes V signal.

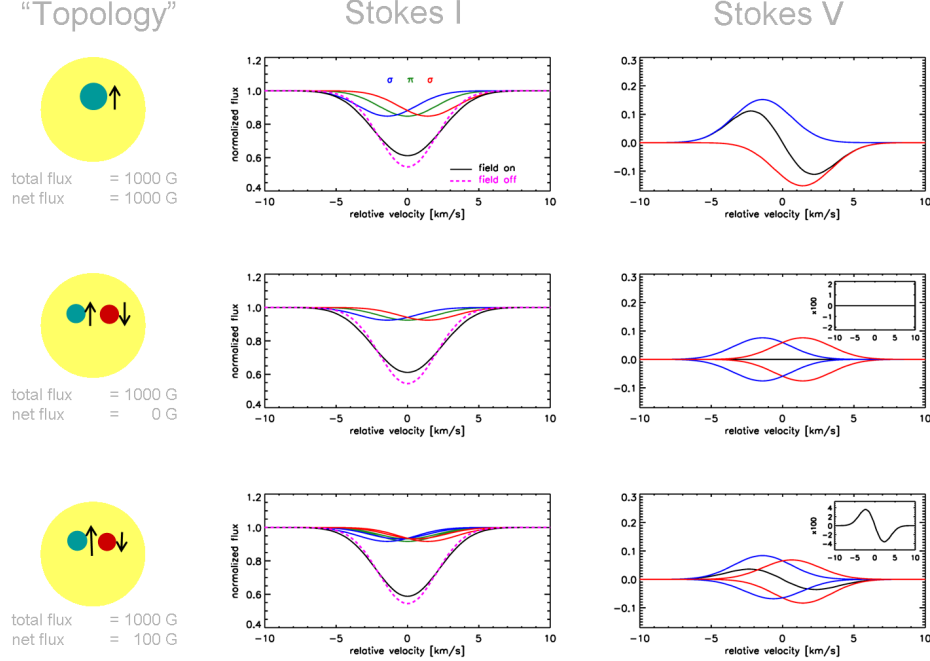


Figure 2. Three examples of simplified field topologies and their signals in Stokes I and V.

Examples of signatures of magnetic fields in Stokes I and V are sketched in Fig. 2. The left panel shows the “topology”, which is actually not the topology of a stellar magnetic field, but nothing else than two areas of radial magnetic fields put on a flat surface (the spherical shape of a star has not been taken into account in this example). In the top row, a simple magnetic field region with only one direction is shown; signed and unsigned “net” flux both are 1 kG in this example. The line in Stokes I is effectively broadened, and Stokes V shows a clear signal on the order of 10 %. Note that the direction of the Stokes V signal indicates the direction of the magnetic field. In the second row, two magnetic regions with only half the size as in the first example are observed. Both regions have the same absolute field strength and area but with opposite polarity. In this example, the Stokes I signal is identical to the first example, but the signal in Stokes V entirely vanishes because the net (signed) flux of this configuration is exactly zero; any field strength in this cancelling configuration is invisible to Stokes V. The last row shows a case in which one of the two areas is slightly larger than the other, the total flux is still 1000 G, but the net flux is only 100 G. The amplitude in Stokes V is ca. 4 %.

2.2. Viewing angle

Another thing that becomes immediately clear is that the geometric interpretation of Zeeman splitting on an unresolved stellar disk can be arbitrarily complicated, no matter if polarized or unpolarized light is used. In addition to the ambiguity between magnetic field strength and filling factor (which includes our ignorance about the number and distribution of magnetic components), the signature of a magnetic field region in stellar spectra depends on the angle between the magnetic field lines and the line of sight (Fig. 1). In reality, again, a distribution of angles will be present because field lines are probably bent on the stellar surface, and because the stellar surface is spherical. As a result, even geometrically relatively simple field distributions will lead to complicated splitting patterns. If the star is rotating (as most stars probably are) that pattern again depends a lot on the time a star is observed – which in turn can be utilized by observing the change of observed spectra with rotation phase.

3. Measurements of cool star magnetic fields

Reliable detections of magnetic fields in cool stars of spectral type F–K are relatively rare, see, e.g., Saar (1996, 2001). The challenges of detecting Zeeman splitting in these stars using atomic lines at optical wavelengths have recently been revisited by Anderson et al. (2010). As realized earlier (e.g., Basri et al. 1990), magnetic field signatures can often be mimicked by the signatures of cool spots so that a definite measurement of magnetic fields, and in particular their distribution and geometry, is a delicate task.

M dwarfs, however, are a bit more cooperative. Although their spectra exhibit a much denser forest of absorption lines rendering it difficult to investigate isolated spectral lines, their magnetic fields can be higher than fields in hotter stars at given rotational velocity $v \sin i$. An important step in our understanding of M dwarf magnetic fields was the investigation of seven M dwarfs by Johns-Krull & Valenti (1996). Line shapes of an atomic Fe I line at 846.7 nm, hidden in a forest of TiO molecular lines, were analyzed and average magnetic field strengths of several kG were reported in a few stars that are probably fully convective (the results of their analysis were updated by those reported in Johns-Krull & Valenti (2000) using a multi-component approach). Complementary work looking for magnetic field signatures in Stokes V was done in T Tauri stars very successfully. Using polarized light, signatures of kG-strength magnetic fields could be discovered (see Johns-Krull 2007).

During the last years, two main routes have been followed searching for direct detections of magnetic fields in M dwarfs. One method is to employ near-infrared molecular absorption lines of FeH to search for Zeeman broadening in Stokes I, another is to extract the polarization signal from several hundred lines at optical wavelengths in order to search for field signatures in Stokes V. Both methods proved to be successful down to the latest M dwarfs, and it is possible to compare the results of both methods in a small number of stars. In the following, an overview on both methods is given and the results are compared and interpreted.

3.1. Results from Stokes I

The spectra of M dwarfs are dominated by the presence of molecular absorption bands. At optical wavelengths, bands from TiO and VO appear. Analysis of Zeeman broaden-

ing in these bands, however, is difficult because the lines are not individually resolved. According to Eq. 1, Zeeman broadening (in terms of velocity shift) is proportional to wavelength, which implies that it is easier to detect at longer wavelength, in particular because other Doppler broadening agents like rotation do not depend on wavelength. At near-infrared wavelengths, a molecular band of FeH can be found in the spectra of M dwarfs, and Wallace et al. (1999) showed that this band is well suited for the measurement of magnetic fields. An observational problem of FeH is that its most suitable band is located at around $\lambda = 1\mu\text{m}$, which is too red for most CCDs and too blue for most astronomically used infrared spectrographs. As a consequence, only very few high-resolution spectrographs can provide spectra of this wavelength, and the efficiencies are typically ridiculously low. On the other hand, M dwarfs emit much of their flux at near-infrared wavelengths so that in comparison to optical wavelengths, the signal quality around $1\mu\text{m}$ is not much lower than around 700 nm if the spectra are obtained with an optical/near-IR echelle spectrograph like HIRES (Keck observatory) or UVES (ESO VLT). The 2004-upgrade of the HIRES spectrograph allowed a thorough test of the FeH spectral range. We developed a method to semi-empirically determine the magnetic fields of M dwarfs comparing FeH spectra of our targets to spectra taken of two template stars; one with no magnetic field and one with a known, strong magnetic field (Reiners & Basri 2006). As reference, spectra of stars with magnetic fields previously measured in a detailed analysis of atomic lines are used (Johns-Krull & Valenti 2000). Thus, all magnetic field measurements are relative to the reference star (Gl 873, $< B > = 3.9 \text{ kG}$), and magnetic fields higher than this value cannot be quantified.

Obviously, systematic uncertainties of the measurements are quite large, typically several hundred Gauss. Unfortunately, Zeeman splitting of the FeH molecule is complicated and cannot entirely be described so far (see Berdyugina & Solanki 2002). Meanwhile, progress has been made using an empirical approach to model Zeeman splitting in FeH lines, and this approach suggests that the fields determined semi-empirically may be overestimated by some $\sim 20\%$ ¹ (Shulyak et al. 2010).

3.1.1. Average fields in M-type stars

Magnetic field measurements in M dwarfs are reported in Saar (1994); Johns-Krull (2007); Reiners & Basri (2007, 2009, 2010); Reiners et al. (2009b,a). This is a non-exhaustive list of publications, and a number of magnetic field measurements of stars re-analysed here can be found in earlier literature (with more or less consistent results); see Saar (1996, 2001). Measurements of M dwarf magnetic fields for spectral types M1–M9 are shown in Fig. 3.

It is well known that early-M dwarfs (M0–M3) in the field are much less active and rotating slower than later, fully convective M stars (e.g., Reiners & Basri 2008). Early-M dwarfs appear to suffer much more effective rotational braking so that their activity lifetime is shorter than in later M dwarfs. Whether this is an effect of different magnetic field topologies in partially and fully convective stars is not clear – this question is one of the basic motivations for the comparison of field measurement results summarized here. It is important to realize that at spectral type M3/M4, several parameters of the stars change dramatically so that the reason for a change in braking timescales may actually be much more fundamental than magnetic field topology.

¹This could be due to an overestimate of the reference magnetic field measurement derived from the atomic line analysis.

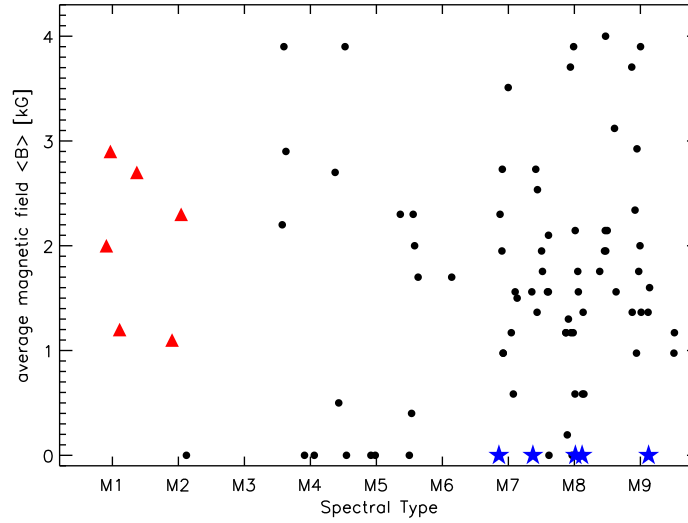


Figure 3. Measurements of M dwarf magnetic fields from Stokes I. Red triangles: young, early M-stars; blue stars: young accreting brown dwarfs; black circles: field M dwarfs. See text for references. Spectral types are offset by a small amount to enhance visibility of different objects.

The field strengths of young, early-M and field mid- and late-M dwarfs are on the order of a few kG. This is the main results from Zeeman analysis and consistently found using different indicators (at least in mid-M dwarfs). Compared to the Sun, the average magnetic field hence is larger by two to three orders of magnitude, an observational result that must have severe implications for our understanding of low-mass stellar activity. It is not clear whether our picture of a star with spots more or less distributed over the stellar surface is actually valid in M dwarfs. If, for example, 50 % of the surface of a star with a mean magnetic field of 4 kG is covered with a “quiet” photosphere and low magnetic field, the other half of the star must have a field strength as large as ~ 8 kG. The two components of the stellar surface on such a star probably have very different temperatures and properties, and the definition of effective temperature must be considerably different from the temperature of the “quiet” photosphere.

In early-M dwarfs (M3 and earlier), magnetic fields were found in young stars that are still rapidly rotating. Since old, early-M dwarfs in the field are generally slowly rotating and inactive there has been no search for magnetic fields in any large sample of them. Typical field values can be expected to be on the level of a few hundred Gauss and less, which is difficult to detect with Stokes I Zeeman measurements.

3.1.2. Young stars and young brown dwarfs

While young, early-M stars exhibit magnetic fields of several kG, which is consistent with the magnetic fields of older M stars rotating at comparable pace and young stars of earlier spectral type, it is surprising that in young brown dwarfs of spectral types M7–M9 only upper limits of a few hundred Gauss could be determined for their magnetic fields (Reiners et al. 2009b) (blue stars in Figs. 3 and 4). Interestingly, all five young brown dwarfs seem to be accretors implying that they still have a disk, and a magnetic field of a few hundred Gauss appears to be enough for magnetospheric accretion in such

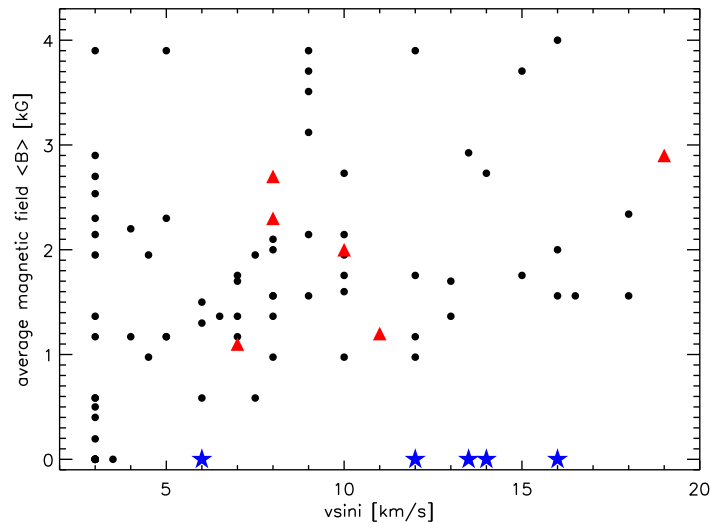


Figure 4. Measurements of M dwarf magnetic fields from Stokes I as a function of projected rotation velocity, $v \sin i$. Symbols are the same as in Fig. 3.

a low-mass object. So far, no direct magnetic field measurement could be performed in non-accreting, old, field brown dwarfs, but it is expected that they also harbor substantial magnetic fields (Reiners & Christensen 2010). Observations of radio-emission indicate that fields of a few kG strength are in fact present on some L-type field brown dwarfs (Hallinan et al. 2008; Berger et al. 2009).

It is an open question whether the non-detection of magnetic fields in brown dwarfs is due to the presence of accretion disks around the objects observed so far. If this is the case, there ought to be some mechanism for the disk to regulate the magnetic field of the central object, which is not easily understood. Alternatively, large difference in radius may be of importance in this context because the surface area of young brown dwarfs is about an order of magnitude larger than the surface of old brown dwarfs. If magnetic flux is approximately conserved during its evolution, the average magnetic field would be an order of magnitude lower in young, large brown dwarfs than in old, small, field brown dwarfs.

3.1.3. Rotation and magnetic fields

Stokes I measurements of magnetic fields are shown as a function of projected surface velocity $v \sin i$ in Fig. 4. The typical signature of a Γ -shaped rotation-activity relation is visible, which means that the lower (left) end of the relation is not resolved because the non-saturated part of the rotation-activity relation falls below the detection limit in rotation velocities. On the other hand, all rapidly rotating ($v \sin i \gtrsim 3 \text{ km s}^{-1}$) field stars show detectable magnetic fields. However, again, the young brown dwarfs violate this relation since they are rapidly rotating but do not show detectable fields.

The rotation-activity relation describes the fact that slowly rotating stars are less active than rapid rotators. In terms of Rossby number, $Ro = P/\tau_{\text{conv}}$, with P the rotation period and τ_{conv} the convective overturn time, stars with $Ro \lesssim 0.1$ are saturated in activity. Stars with larger values of Ro show activity proportional to Ro . We know from the Sun that activity is caused by magnetic fields, and a rotation-magnetic field

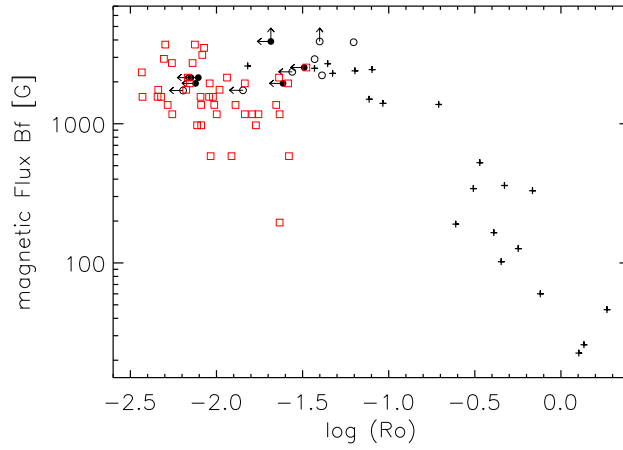


Figure 5. Magnetic fields as a function of Rossby number. Crosses and circles are stars M6 and earlier (see Reiners et al. 2009a, and references therein). Red squares are objects of spectral type M7–M9.

relation was shown by Saar (1996). At that time, however, magnetic fields could not be measured in stars with very low Rossby numbers (saturated regime) because spectral line widths are too broad due to the rotational broadening occurring at these velocities. M dwarfs, on the other hand, have very small radii (and long overturn times) so that for low Rossby numbers the corresponding surface velocities are relatively low. This allows measuring magnetic fields of stars well within the saturated regime. For M dwarfs of spectral type M6 and earlier, it was found that average magnetic fields indeed saturate (Reiners et al. 2009a). This implies that the saturation of the rotation-activity relation is due to a saturation of the average magnetic field and that B itself is limited (in contrast to a limit in the filling factor f only).

Recently, we have measured magnetic fields in a sample of M7–M9 stars (Reiners & Basri 2010). These measurements are shown as red squares in Fig. 5. Stars as cool as M7 seem to deviate from the rotation-activity relation; they still show higher magnetic fields at lower Ro , but saturation seems to occur at much lower values of Ro .

3.2. Results from Stokes V

Maps of magnetic fields in M stars derived from time-series of Stokes V measurements are presented in Donati et al. (2008); Morin et al. (2008, 2010). The Stokes V profiles are derived simultaneously from several hundred lines through least-squares-deconvolution (LSD). LSD makes use of the weak-field approximation so that very strong magnetic fields (several kG) may not be detectable with this method. As mentioned above, the use of only Stokes V means that the magnetic geometry will not be fully characterized. In particular, magnetic regions of opposite polarity can cancel each other so that they remain undetected. A way to overcome this issue is to take observations at different times so that magnetic regions may remain visible when they appear at the limb of the star (Zeeman Doppler Imaging, ZDI). The resolution of such a Doppler image critically depends on the rotation velocity of the star and the exposure time required to obtain the necessary data quality.

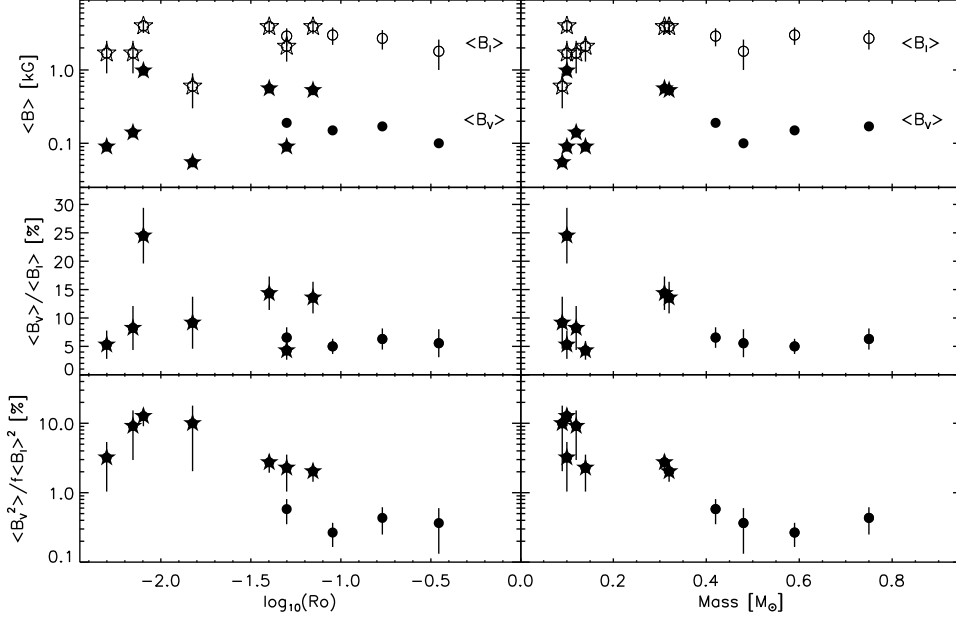


Figure 6. Measurements of M dwarf magnetic fields from Stokes I and Stokes V. *Top panel:* Average magnetic field – Open symbols: measurements from Stokes I; Filled symbols: measurements from Stokes V. *Center panel:* Ratio between Stokes V and Stokes I measurements. *Bottom panel:* Ratio between magnetic energies detected in Stokes V and Stokes I. Circles show objects more massive than $0.4 M_{\odot}$, stars show objects less massive than that.

A tremendous amount of work was put into the analysis of magnetic geometries in stars through ZDI, and the possibility of reconstructing magnetic fields on stellar surfaces is truly amazing. However, the interpretation of the field maps is very difficult, and conclusions have to be drawn with great care.

3.2.1. Magnetic field strengths

Typical average magnetic field strengths found in Stokes V measurements of M dwarfs are about a few hundred Gauss. Note that this is the average value for the detected unsigned magnetic field, $|B|$, the same as in Stokes I measurements; the average value of the signed magnetic field is zero by construction. An average field strength of a few hundred Gauss is much lower than average field strengths of magnetically active stars observed in Stokes I that are a typically few kG. The literature today contains eleven M dwarfs for which magnetic field measurements were carried out independently both in Stokes V and Stokes I. I compare the results from the mentioned papers in Fig. 6, which is an update of Fig. 2 in Reiners & Basri (2009).

Fig. 6 shows the average magnetic fields from Stokes I and V, their ratios, and the ratios of magnetic energies as a function of Rossby number and stellar mass. In the top panel, the measurements are shown directly, the center panel shows the ratio between the average magnetic fields $\langle B_V \rangle / \langle B_I \rangle$. For the majority of stars, the ratio is on the order of ten percent or less, which means that $<10\%$ of the full magnetic field is detected in the Stokes V map. In other words, more than 90 % of the field is invisible

to this method. As discussed above, this is probably a consequence of cancellation between field components of different polarity. One notable exception is the M6 star WX Uma, which has an average field of approximately 1 kG in Stokes V (Gl 51 shows an even higher field but has not yet been investigated with the Stokes I method).

A second observable that comes out of the Stokes V maps is the average squared magnetic field, $\langle B^2 \rangle$, which is proportional to the magnetic energy of the star. Under some basic assumptions, this value can be approximated from the Stokes I measurement, too (see Reiners & Basri 2009). The ratio between approximate magnetic energies detected in Stokes V and I is shown in the bottom panel of Fig. 6, it is between 0.3 and 10 % for the stars considered.

3.2.2. Topologies of the detected fields

In contrast to the conclusions suggested in Donati et al. (2008) and Reiners & Basri (2009), evidence for a change in magnetic topologies at the boundary between partial and complete convection is not very obvious when the new results are included. Four of the late-M dwarfs have ratios $\langle B_V \rangle / \langle B_I \rangle$ below 10 % while earlier results suggested that more flux is detectable in Stokes V in fully convective stars. On the other hand, the ratio of detectable magnetic energies stays rather high in this regime ($\gtrsim 2\%$), which may reflect an influence of the convective nature of the star. The main problem, however, seems to be why some stars have very different ratios $\langle B^2 \rangle / \langle B \rangle^2$. This may well be an effect of different magnetic topologies but large differences occur even within the group of fully convective stars (see Morin et al. 2010).

4. Summary

Our knowledge on magnetic fields in cool stars, particularly in M stars across the full convection boundary, has seen enormous progress during the last few years. Intensive observations of many M dwarfs led to the construction of Stokes V Doppler maps, and the exploitation of the FeH molecular spectra allow a determination of the entire field from Stokes I. We can now start to compare results from independent methods and search for the influence of stellar parameters including convective nature. The interpretation of results from different methods opens a parameter space that certainly contains deep information about the fields and their topology, but it is not yet clear what our measurements are actually telling us. Field strengths and topologies have ramifications to a broad range of astrophysics, and at spectral type late-M, we are approaching the brown dwarf regime. More field measurements, determination of molecular constants, and fundamental investigation of detectabilities are required to push the field forward, and to understand the many facets of magnetic fields in cool stars, brown dwarfs, star formation, and their links to exoplanets.

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